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Energy and environmental assessment of a traditional durum-wheat bread

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ABSTRACT

This study was designed and developed to investigate the bread sector, by addressing the environmental issues associated with the supply chain of '*Pagnotta del Dittaino*', a Protected Designation of Origin (PDO) durum wheat bread produced in the central-east area of Sicily.

In particular, the study discusses the application of Life Cycle Assessment (LCA) to highlight the most significant and representative environmental impacts for this bread production system. Cumulative Energy Demand (CED) and Carbon Footprint (CF) were also estimated to address the usage of primary-energy sources and the emissions of GreenHouse Gases (GHGs).

Cultivation is the system hotspot, mostly because of the production of urea and diammonium phosphate, and of the agricultural activities. Significant contributions arise from ammonia volatilisation and nitrous oxide emission due to mineral fertilisation, affecting *'Human health'* and *'Climate Change'*. '*Resources*' were impacted by the non-renewable energy use (natural gas and crude oil) which, in turn, is due to the production and transport of fertilisers and to the agricultural activities. Additionally, the CED-analysis highlighted the important contribution made by the use of biomass energy, as a consequence of the energy sequestered by the plant during growth. CO_2 resulted to be the most relevant and representative GHG in this food system.

The study contributes to the subject knowledge and literature, and can be of interest for researchers, LCA practitioners, farmers and producers, policy makers and other stakeholders, and could support the implementation of environmental labels.

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1. Introduction

Bread is by now accepted worldwide to be a staple product: every country has its own specially breads, which differ from each other for specific shapes, colours, textural and organoleptic properties determined, in turn, by the most diverse ingredients and processes. Amongst ingredients, cereals, water, yeast and salt are the basic components, which can be accompanied by vegetable or animal fats, and other side-ingredients used in traditional preparations. Designations of origin are increasingly attracting the interest of consumers who demand quality and traditional products. Protected Designations of Origin (PDO) and Protected Geographical Indications (PGI) refer to those products whose characteristics are intrinsically linked to their geographical origin (Reg. UE 1151/2012). PDO products often represent niche productions and aim at widening the potential of these local productions worldwide. Nowadays, data on environmental sustainability are increasingly becoming important for a better identification and evaluation, and a greater appreciation and competitiveness of products in the global market. This emphasises upon the urgent need for assessments to help producers identify the environmental burdens generated by their products inside and outside the factory gate, and make changes for improvement. Consumers are increasingly basing their demands on quality and sustainability of products, thus influencing the global market. Moreover, increased knowledge on the environmental impacts of productions, with special regards to

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staple foods such as bread, will significantly contribute to the global objective of moving towards a more sustainable society (Ingrao et al., 2016).

In this context, the Life Cycle Thinking (LCT) approach represents the foundation to assess the improvements that can be made all along the supply chain for high quality and sustainability foods. Life Cycle Assessment (LCA) is acknowledged worldwide to be a valid tool for this purpose: it substantiates the LCT approach by a clear and structured methodology which is ruled by the International Standards 14040 and 14044 (ISO, 2006 a,b). It is a systematic tool enabling qualification and quantification of the environmental impacts associated with a product in its life cycle (Ingrao et al., 2015), through the evaluation of several indicator, such as global warming, non-renewable energy, respiratory inorganic matter, acidification and eutrophication, eco-toxicities, and land occupation.

The present work was developed to investigate the production and packaging of a Sicilian PDO DW bread, called '*Pagnotta del Dittaino*', as the need for and pathway to highlighting environmental criticalities and improvement potentials.

Finally, the study consisted in the application of LCA for the assessment of the global environmental impact, along with both Cumulative Energy Demand (CED) and Carbon Footprint (CF) for more in-depth addressing the usage of primary-energy sources and the emissions of GreenHouse Gases (GHGs).

2. Energy and environmental assessment in the bread production field: a literature review

Environmental studies of food products have been limited by the complexity of agricultural and food systems: in recent years, however, the development of databases and detailed inventory data on the various phases of life cycles has helped the implementation of such studies and boosted the availability of data on a wide variety of products. Indeed, environmental information on widely consumed products covers special importance, due to the impacts generated worldwide and to the potential global effects that improvements in the life cycle could bring.

Andersson and Ohlsson (1999) compared different bread production scales and their environmental effects by LCA. Even if this seems to be the first comprehensive LCA study on bread, the methodology, with special regards for the system boundaries, significantly differs from actual approaches. This was due, for instance, to the lack of inventory data at the time of publication, which did not allow the consideration of some impacts related to cultivation (e.g.: production and use of pesticides, assimilation of CO_2 by crops, leakage of phosphorous and gaseous emissions from the fields). Results showed that the overall impacts generated by the different production scale systems did not differ significantly, and that the same hotspots could be identified for all production scales, with food processing, agricultural phase and transportation determining the highest burden on most of the impact categories considered.

In another study, Braschkat et al. (2004) evaluated the environmental performances of bread produced at different scales, which were combined with other variables, to give eight different scenarios. The authors assessed the effect of the crop management and found that organic management lowered the impact for all of the considered categories except for land area required, as a consequence of the lower yields. In this study, baking was the hotspot for energy demand and greenhouse effect, whilst cultivation represented by far the highest burden for most impact categories. Industrial milling coupled with industrial bread-making was the most preferable scenario, however, special attention should be paid to the role of transportation (of grains, flour and purchased bread) on the overall impact of bread production.

The effect of crop management on the environmental impact of bread was also assessed by Meisterling et al. (2009), who confirmed the general advantages of wheat organic production compared to conventional management, highlighting that the latter causes about 16% more CO_2 equivalents emission. The paper illustrated the burden of transportation on the global environmental impact of bread, and suggested that 2000 km distance had a Global Warming Potential (GWP) comparable to that of the whole bread production, not including shipping. The authors finally suggested that best management practices could significantly contribute to decreasing GWP by minimising N_2O emissions and carbon sequestration.

More recently, Espinoza-Orias et al. (2011) performed a LCA study on bread, addressing the effects of wheat origin, type of flour and packaging. In every case considered, the highest contribution to CF was given by the wheat cultivation stage (about 35%), followed by bread consumption (about 25%). To these regards, authors highlighted that sliced white bread in UK is commonly toasted, this operation significantly affecting the global energy use for the produce life cycle. Regarding the effect of wheat origin, the production of bread from wheat sourced in UK had the lowest CF, whilst the use of 20% wheat from Spain determined the highest impact: this is because of lower yields, whilst transport did not affect results significantly. Interestingly, also the flour type had significant effects, with wholemeal bread contributing 6–7% less to CF compared to white bread. The study also pointed out that smaller loaves required increased use of packaging, but this additional impact would be easily counterbalanced by the potential food waste reduction.

As for Braschkat et al. (2004) and Meisterling et al. (2009), Moudry et al. (2013) observed that organically produced wheat allowed the reduction (by about 12%) of greenhouse gas emissions compared with conventional farming, and remarked the role of transport in the overall impact associated with bread production, reporting that extra-regional transport accounted for as much as 0.11 kg CO_2 equivalents. In this study, the highest emission load was attributed to processing, followed by the agricultural phase and by a minor, though significant, contribution of transport (by comparison between regional and imported wheat).

A recent LCA study performed on bread from different food networks in Europe (Kulak et al., 2015) aimed at assessing the effect of low-input farming, on-farm processing and direct distribution. The variability in the conditions of the case studies considered did not allow to determine general hotspots. However, for most of the considered networks, the agricultural phase represented the highest burden, as far as GWP was concerned. In some cases, baking also represented a significant impact phase whilst, for a small-scale labour-intensive production, the advantage at the agricultural stage was offset by higher impacts for milling, baking and distribution. No correlation could be demonstrated between low-input farming and sustainability, on the other hand, the reduced recourse to inputs often determined lower yields which, in turn, negatively impacted environmental performance. The study pointed out the difficulty of comparing different systems, due to specific site conditions and individual management decisions. Some networks alternative to the industrial model had higher environmental impacts compared to the reference system. Hence switching to alternative supply chains does not always guarantee environmental benefits: the study highlighted the importance of the distribution phase, which could counterbalance the positive sides of small-scale and low-input systems.

The most recent report on the environmental evaluation of bread compared 21 different types of bread produced in the European Union (Notarnicola et al., 2017). As one could expect, the environmental performance is affected by the composition, hence breads made with simple ingredients (flour, water and yeast) had the lowest impacts, when a mass based Functional Unit (FU) was

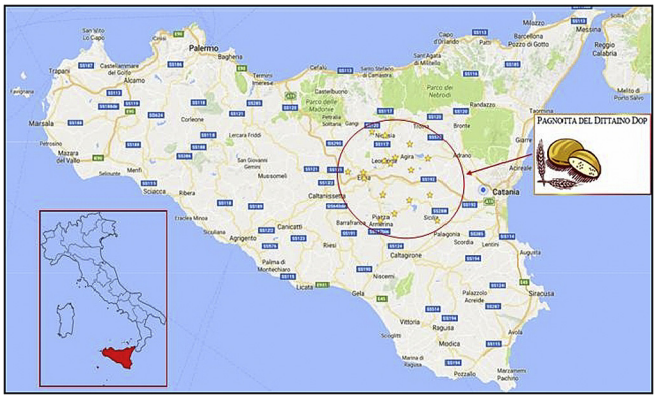


Fig. 1. Localisation of the production area of '*Pagnotta del Dittaino*' PDO DW bread. Stars indicate the 17 municipalities head of the territories included in the production specifications (EU 613/2014).

considered. However, when assessing the products on an energy based FU, receipts including vegetable or animal fats were more environmental friendly. In any case, the agricultural phase, in agreement with previous reports, represented the highest burden, especially due to the use of fertilizers and pesticides (Renzulli et al., 2015); similarly, baking was confirmed as another hotspot in the process, due to high energy consumption.

Based upon the review performed, it can be concluded that a limited number of studies have been published in almost twenty years to address the environmental performance of wheat bread: just seven papers were found, indeed, in the subject literature. Additionally, none of those has addressed neither DW nor PDO breads, so highlighting, according to this author team, the novelty and the scientific relevance of this study, as well as the contribution that it can make in the field, subsequently.

3. The *'Pagnotta del Dittaino'* PDO*: main features and production process*

Durum Wheat (DW) often represents the base for breads produced in the Mediterranean basin. DW breads, especially those obtained by natural fermentation (yeast-base starter), are characterised by peculiar sensory and textural properties (Pasqualone et al., 2004; Pasqualone, 2012) and by a slower staling rate which, in turn, is allowed by the higher water binding capacity compared to normal wheat (Boyacioglu and D'Appolonia, 1994; Quaglia, 1988; Licciardello et al., 2013). DW breads, hence, achieve longer shelf lives, which can be further extended with suitable packaging systems (Licciardello et al., 2014, 2017).

The *'Pagnotta del Dittaino'* PDO is a DW bread obtained by sourdough fermentation. It is produced in the territory of 17 municipalities of central-eastern Sicily, Italy (Fig. 1), an area that is traditionally well-suited for DW production. It is characterised by a 3-4 mm-thick crust and a pale yellow, fine-grained, uniform and compact crumb. The moisture of this bread does not exceed 38%, and its sensory characteristics are preserved for about 5 days, as a result of the use of DW semolina and sourdough fermentation.[1]

The name was entered in the register of PDOs and PGIs under class 2.4 with Regulation EU 516/2009. The production specifications (EU 613/2014) detail agricultural and technological requirements together with a description of the product major characteristics.

Sourdough fermentation (Pulvirenti et al., 2004) is often preferred to the use of baker's yeast, based on some advantages such as the development of peculiar flavours, the improved sensory quality and a slower staling rate. Sourdough fermentation is based on the use of a natural yeast originating from a "mother sponge" which is daily refreshed. For the daily refreshment of sourdough used for production of the *'Pagnotta del Dittaino'* PDO bread, one part of "mother sponge" is mixed with two parts of semolina and one part of water: the dough obtained is portioned into 4 parts, three of which, after a rest for 5 h, serve as the natural leaven (*criscenti*) for the breadmaking of the day; the remaining part becomes the new "mother sponge" which will be chill-stored in a dedicated chamber and renewed 24 h later. Whether bread is produced or not, the "mother sponge" has to be refreshened, in order to maintain its properties and active state.

The *'Pagnotta del Dittaino'* PDO bread is produced by baking the dough obtained mixing DW semolina, water, sourdough and salt in the following proportions: semolina: 100 kg; water: 58–70 l (depending on the gluten and moisture content); sourdough: 15–18 kg (depending on the environmental temperature); salt: 1.5–2.0 kg. Kneading is performed by plunging arms mixer for about 12 min: following, the dough rests for 5 min before being shaped (manually or automatically) and leavened. Dough shaped into loaves is leavened for 120–180 min at 30–32 °C and 58–63% R.U, then the loaves are baked at 230 °C for 40–60 min and cooled before packaging.

The whole supply chain, from DW grain production to bread production and packing, is presented in Fig. 2.

4. Materials and methods

In this study, LCA was elaborated according to the specific International Standards (ISO, 2006 a,b), and so was articulated in the following four phases: Goal and Scope Definition; Life Cycle Inventory (LCI); Life Cycle Impact Assessment (LCIA); and Life Cycle Interpretation. For a better understanding and appreciation of the study conducted, the development of each of those phases has been discussed in the sections below.

4.1. Goal and scope definition

In this study, LCA, CF and CED were performed, with a from-cradle-to-gate approach, to investigate from an energy and environmental perspective the supply chain of a Sicilian PDO DW bread, named *'Pagnotta del Dittaino'*. It was developed in the light of the influence that such a food product has on the agro-economy of the Region, so as to be considered as one of its most representative foods. Such a study is also warranted by a lack of LCAs and related assessments in the field of DW breads, as documented in the review performed, so emphasising upon the need for studies enriching the subject literature and databases. LCA, CF and CED were used in this study because they are widely recognised as key methods for the assessment of environmental sustainability indicators in food production systems. Therefore, through application of those methods the study aims at highlighting the energy and environmental hotspots associated with the system investigated, as the starting point to stimulate operating improvements for their reduction.

In this phase, the FU and the system boundaries were defined following the subject International Standards (ISO, 2006 a,b). In particular, the FU is the key element that represents the unit of product and provides a reference through which inputs are linked to outputs and related impacts (Arzoumanidis et al., 2013; Robertson, 2013).

The system boundaries establish which unit operations should be considered when assessing the life cycle of a product (Arzoumanidis et al., 2013). Those operations are generally

[1] Reproduction of the brand by courtesy of the '*Pagnotta del Dittaino*' PDO Producers Association.

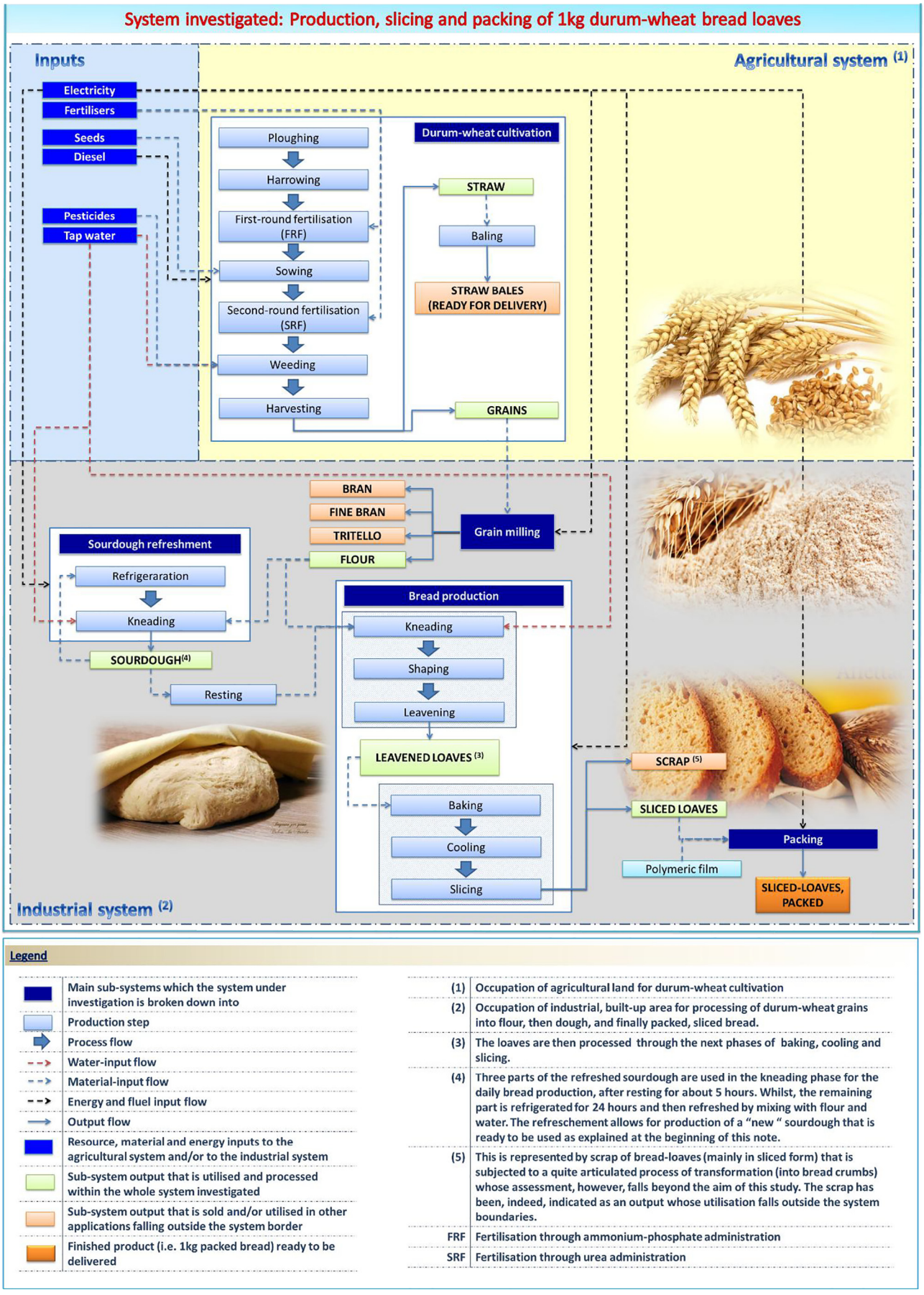

System investigated: Production, slicing and packing of 1kg durum-wheat bread loaves
Inputs
Agricultural system (1)
Electricity
Fertilisers
Seeds
Diesel
Pesticides
Tap water
Durum-wheat cultivation
Ploughing
Harrowing
First-round fertilisation (FRF)
Sowing
Second-round fertilisation (SRF)
Weeding
Harvesting
STRAW
Baling
STRAW BALES (READY FOR DELIVERY)
GRAINS
BRAN
FINE BRAN
TRITELLO
FLOUR
Grain milling
Sourdough refreshment
Refrigeraration
Kneading
SOURDOUGH(4)
Resting
Bread production
Kneading
Shaping
Leavening
LEAVENED LOAVES (3)
Baking
Cooling
Slicing
SCRAP (5)
SLICED LOAVES
Packing
Polymeric film
SLICED-LOAVES, PACKED
Industrial system (2)
Legend
Main sub-systems which the system under investigation is broken down into
Production step
Process flow
Water-input flow
Material-input flow
Energy and fluel input flow
Output flow
Resource, material and energy inputs to the agricultural system and/or to the industrial system
Sub-system output that is utilised and processed within the whole system investigated
Sub-system output that is sold and/or utilised in other applications falling outside the system border
Finished product (i.e. 1kg packed bread) ready to be delivered
(1) Occupation of agricultural land for durum-wheat cultivation
(2) Occupation of industrial, built-up area for processing of durum-wheat grains into flour, then dough, and finally packed, sliced bread.
(3) The loaves are then processed through the next phases of baking, cooling and slicing.
(4) Three parts of the refreshed sourdough are used in the kneading phase for the daily bread production, after resting for about 5 hours. Whilst, the remaining part is refrigerated for 24 hours and then refreshed by mixing with flour and water. The refreschement allows for production of a "new " sourdough that is ready to be used as explained at the beginning of this note.
(5) This is represented by scrap of bread-loaves (mainly in sliced form) that is subjected to a quite articulated process of transformation (into bread crumbs) whose assessment, however, falls beyond the aim of this study. The scrap has been, indeed, indicated as an output whose utilisation falls outside the system boundaries.
FRF Fertilisation through ammonium-phosphate administration
SRF Fertilisation through urea administration

Fig. 2. Boundaries of the system investigated.

Table 1
Inventories associated with the cultivation phase.

Outputs			
Output products	*Amount*	*Unit of measure*	*Comment*
Grains	**1**	kg	The values alongside were calculated considering that the core product for the DW cultivation phase is 1 kg grain. In addition to this, according to the farmer, the gross production yield is equal to 4500 kg/ha and is distributed as follows: 3000 kg/ha, grains; and 1500 kg/ha, straw. This means that: 0.5 kg of baled straw are obtained per each kg of harvested grains; and a total gross-production (grains + straw) of 1.5 kg is obtained, which all inputs below were referred to. The related surface invested was calculated multiplying the gross-production yield reverse (2.22E-4 ha/kg) by the gross production considered in this study (1.5 kg), and a value of 3.33E-4 ha was obtained (surface corresponding to a 1.5 kg gross-production).
Straw	**0.5**		Finally, using a mass-based allocation criterion, the damage associated with the cultivation system has resulted to be allocated as follows: 66.67%, grains; and 33.33% straw.
Inputs			
Resources	*Amount*	*Unit of measure*	*Comment*
Arable, non-irrigated land	**3.33E-4**	ha	This is the piece of land that is invested for DW cultivation
Energy, gross calorific value, in biomass	**22.707**	MJ	Both energy and CO_2 are sequestered during plant growth. The alongside values were extrapolated from Ecoinvent and referred to the gross-production (1.5 kg).
Carbon dioxide (CO_2), in air	**1.943**	kg	
Materials	*Amount*	*Unit of measure*	*Comment*
Seeds	**0.075**	kg	As provided by the farmer, the requirements per ha of cultivated field is equal to 225 kg; from this value, the one alongside was calculated. The production of 1 kg DW seeds was modelled putting the DW cultivation together with the processing (from treating to storage). In particular, the former phase is the one discussed in this table. It was modelled using primary data provided by the farmer combined with secondary data extrapolated from Ecoinvent, and whose inputs were detailed in this table. Whilst, the processing phase was modelled using background data extrapolated from Ecoinvent ('Wheat seed IP, at regional storehouse). In particular, it was represented in terms of: the DW grains (or seeds) at the farm gate (1 kg); electricity consumption for the processing of the seeds (0.024 kWh per kg of seeds); the share of the multi-storey building where the processing plant is located (2E-5 m^3 per kg of seeds); and the transport for supply of the harvested DW grains (or seeds) to the processing plant, travelling for the local distance of 15 km. Packing of the seeds was neglected as they are sold and transported in bulk form. Finally, transformation to and occupation of industrial, and built-up areas were considered according to the Ecoinvent model.
Diammonium phosphate, as N, at regional storehouse	**0.03996**	kg	The alongside values were calculated based upon total requirements per ha of cultivated field equal to 200 kg. The latter was then referred to the field share associated with 1.5 kg gross-production (i.e. 3.33E-4 ha), and the value of 0.0666 kg was calculated. This value was then split out based upon the contents of N (18%) and P_2O_5 (46%) in the diammonium phosphate fertiliser. This was done using the multioutput-process contained in Ecoinvent, 'diammonium phosphate, at regional storehouse', which delivers the co-products: 'diammonium phosphate, as N, at regional storehouse'; and 'diammonium phosphate, as P_2O_5, at regional storehouse'. The allocation factors, that are considered by the database based upon the energy requirements of the respective nutrients for the production processes, are: 60% for 'diammonium phosphate, as N, at regional storehouse'; and 40% for 'diammonium phosphate, as P_2O_5, at regional storehouse''. As recommended by Ecoinvent, the allocated inventories were used simultaneously. So, the amount of diammonium phosphate as N was calculated as 60% (0.0666 kg), whilst that of diammonium phosphate as P_2O_5 as 40% (0.0666 kg).
Diammonium phosphate, as P_2O_5, at regional storehouse	**0.02664**	kg	
Urea	**0.0533**	kg	The requirements per ha of cultivated field is equal to 160 kg (primary data provided by the farmer); from this value, the one alongside was calculated. The Ecoinvent module 'Urea, as N, at regional storehouse' (with a 46% N content) was considered for the modelling of the urea production phase.
Pesticide	**1.332E-4**	kg	The pesticide that is administered by farmers in the DW cultivation phase is based upon mesosulfuron-methyl and iodosulfuron-methyl-sodium. However, that has not been found in the list of pesticides contained in the database. So, the Ecoinvent model 'Pesticide unspecified, at regional storehouse', that uses average data on resources, materials, energies and emissions. This was done considering the little amount of pesticide utilised (see value alongside), and the low environmental impacts expected compared to the other phases.
Dilution water	**0.1665**	kg	Tap water used for pesticide administration.
Agricultural treatments	*Amount*	*Unit of measure*	*Comment*
Ploughing Harrowing Fertilising Sowing Weeding Combined harvesting	**3.33E-4**	ha	The alongside phases were implemented using models already contained in Ecoinvent: the FU in each of them is 1ha of treated soil. It is clear that each of those agricultural-activity related models was inputted to the cultivation phase using the value of 3.33E-4 ha which, as a reminder, is referred to 1.5 kg gross production. Additionally, in each of those modules the inventory takes into account the diesel fuel consumption and the amount of agricultural machinery and of the shed, which has to be attributed to the single agricultural activity. Also taken into consideration is the amount of emissions to the air from diesel combustion and the emission to the soil from tyre abrasion during the work process. However, checking within the aforementioned models the authors have realised that adjustments were needed. In particular, the diesel consumption values were modified inputting those provided by the farmer, and the values of the emissions (including those of greenhouse gases) resulting from combustion of those diesel amounts were updated subsequently. This was done by proportioning the emission values already present within those models to the diesel consumption values specifically provided by the farmer, except for the. harrowing treatment, whose actual diesel consumption coincides with the one contained in the related Ecoinvent model.

Table 1 (*continued*)

			In particular, from interviews with the farmers and agronomists it was recorded that, on an average basis: - ploughing is performed once a year with a diesel consumption equal to almost 12 kg/ha; - harrowing is done twice a year with a total consumption of diesel equal to 11.48 kg/ha; - two rounds of fertilisation are carried out, with a diesel consumption of 2.46 kg/ha each (almost 4.9 kg/ha in total); - sowing consumes almost 4.9 kg/ha of diesel; - weeding is done once a year and the related diesel consumption is 2.46 kg/ha; - combined harvesting is conducted at the end of the farming cycle and requires a consumption of diesel equal to 20.5 kg/ha. For each of these activities, the related background data in Ecoinvent were the following: - ploughing, 26.1 kg/ha; - harrowing (by rotary harrow), 11.5 kg/ha; - fertilising (by broadcaster), 5.29 kg/ha; - sowing, 3.82 kg/ha; - application of plant protection chemicals by field sprayer (weeding), 1.76 kg/ha; - combined harvesting, 33.3 kg/ha. So, except for the harrowing process, the following correction factors were used to adjust the GHG emissions from diesel combustion, and so adapt the single agricultural activity model to the specific case: - ploughing, 0.471; - fertilisation, 0.93; - sowing, 1.288; - weeding, 1.398; - harvesting, 0.616. It should be observed that corrections have not been made upon the emissions to the soil from tyre abrasion. This is because they are dependent not upon the diesel consumption issue but upon the agricultural machineries utilised and the conditions in which they are utilised. This issue was neglected as those conditions are unknown. Also, data and information about the eventual differences in machineries considered in those modules compared to those used in the system under study are not available for operating the related changes; nevertheless, the differences in environmental impact magnitude were expected to be highly negligible compared to the other issues, processes and phases.
Straw baling	**7.126E-4**	p	The process was modelled using the module already contained in Ecoinvent, 'Baling/CH U': the related functional unit is represented by one round-bale that is expressed as 1p. However, adjustments were required to make the model suitable for application in the present case-study. It was observed that those considered in the database are 1.4 m^3, 700 kg bales, whilst those concerning to the system investigated are 1.8 m^3, 300 kg bales. Therefore, a mass-based correction factor of 0.428 was calculated and used for correctly computing all the inputs and outputs considered by Ecoinvent for the baling process. In addition, the HDPE wrapping foil has not been considered as the bales are not ensilaged in this system. Changes in the diesel consumption have not been made as the value (per round-bale) contained in the Ecoinvent baling-model (i.e. 0.743 kg) is largely comparable to that provided by the farmer. Therefore, the differences in terms of the amounts of emissions from diesel combustion were neglected. That diesel-consumption value is referred just to the bale preparation phase. This is because, once created, the bales are left on the ground, waiting to be loaded into trailers and transported to the potential users. These two stages were, indeed, considered by the authors as pertaining to the downstream phases of utilisation and processing of those bales. For this reason, they were considered to fall outside the system boundaries and so have not been accounted for in the assessment. Finally, for greater understanding, it is explained that the value alongside was calculated as $0.428 \times N_{bales} \times S_{GP}(1.5)$, where: - 0.428 is the correction factor considering the difference in bale mass between the Ecoinvent model and the specific case; - N_{bales} is the number of bales that are produced per ha of cultivated field (5, considering that the straw production yield is equal to 1500 kg/ha and a single bale mass is equal to 300 kg); and - $S_{GP(1.5.)}$ is the surface associated with 1.5 kg gross-production (i.e. 3.33E-4 ha).
Emissions from fertilised soil	*Amount*	*Unit of measure*	*Comment*
Ammonia (NH_3) Dinitrogen monoxide (N_2O)	**0.00405** **3.462E-4**	kg	NH_3 volatilisation and N_2O emissions are a consequence of the on-field application of mineral fertilisers. In particular, it was documented that nearly 80% of the N_2O emissions due to agriculture are related to the use of mineral and organic fertilisers (Brentrup et al., 2000). Therefore, the authors have decided to compute these two emission sources. Calculations were developed following duly the methodology proposed by Brentrup et al. (2000).

represented by the extraction of resources, the production of materials and energies, and other processes characterising the system investigated.

Both the FU and the system boundaries were defined in this study to: be consistent with the aim and scope of the study; best represent the system under investigation; facilitate data collection; and enable comparisons with quite similar breads, whether existing.

The FU was chosen to be 1 kg packed sliced bread loaves and the systems boundaries included: the preparation of both input materials and energies from resource extraction; their transformation into the finished product (1 kg packed sliced bread loaves); and its packing. According to Clasadonte et al. (2013), the system boundaries were defined based upon the organisational, managerial and technological aspects related to the supporting firm. This was done to best understand all the processes and stages of the system, and the way the input and output inventories as well as the environmental impacts were quantified and analysed.

The reader is referred to Fig. 2 where those system boundaries

Table 2
Inventories associated with the grain milling phase.

Outputs			
Output products	*Amount*	*Unit of measure*	*Comment*
Semolina	**1**	kg	The values alongside were calculated considering that the core product for the milling phase is represented by 1 kg semolina. The process delivers also bran, fine bran and tritello which were modelled as co-products, in that they have a market value as such or in the form of the products into which they are transformed. So, the damage associated with this phase was allocated to the product and the co-products according to a mass-based criterion; here are the allocation percentages thus obtained: 79%, semolina; 8.7% bran; 8.2% fine bran; and 4.1% tritello. The inputs listed in this table are related to the milling phase and so are common to both product and co-products.
Bran	**0.11**		
Fine bran	**0.104**		
Tritello	**0.052**		
Inputs			
Materials	*Amount*	*Unit of measure*	*Comment*
Grains	**1.266**	kg	All the inputs and outputs, as well as the environmental impacts associated with the grain production phase are proportioned to the value alongside, which is required for 1 kg semolina production.
Electricity	**0.127**	kWh	This is the electricity required for the milling of 1.266 kg DW grains. It is a medium voltage electricity whose production was modelled using background datasets available in Ecoinvent. The inventory takes into account the electricity production in Italy and from imports, the transmission network and direct SF6-emissions to air. Electricity losses during medium-voltage transmission and transformation from high-voltage are accounted for. Furthermore, this dataset describes the transformation from high to medium voltage as well as the transmission of electricity at medium voltage. Finally, the reader should be informed that the entire transformation process, from the milling to the bread production and packing, is developed in the same factory and so is fed with the same type of electricity. Therefore, for avoiding double information, no description of this Ecoinvent module of electricity will provided in the next tables.

were detailed. The whole system was split into the following five sub-systems: DW grain cultivation; grain milling; sourdough refreshment; bread production; and packing. Also, there is evidence that a distinction was done between: the sub-system outputs that are processed within the system boundaries (i.e. DW grains, semolina, sourdough, and sliced-bread); and those that fall outside the system boundaries (i.e. the straw and the milling by-products) and are used for applications that do not pertain to this study. With regard to the phases of wheat farming and milling, mass-based allocations were performed using the information provided by farmers and technicians: those have regarded the type and amount of each of those products and co-products.

4.2. Life Cycle Inventory analysis

This phase is acknowledged worldwide to be the most consuming part in LCA, as it involves compilation, qualification and quantification of both inputs and outputs. The inputs are represented by the resources, materials and energies that are utilised in the system investigated, whilst the outputs are the material emissions in air, water and soil, as well as the exploitation of natural and primary-energy resources.

In this context, since a specialised system was investigated, priority was given to the use of site-specific data (primary data) that regarded both typologies and amounts of those inputs and outputs.

The primary data were provided by the bread production company that supported the study development. They were collected through interviews with the firm technicians and check-lists, implemented for the case, which were filled in during production-site investigations. Then, they were combined with background data, extrapolated from databases of acknowledged scientific value and relevance, like Ecoinvent. The latter was used because it is recognised worldwide as accommodating most of the background materials and processes often required in LCAs (Frischknecht and Rebitzer, 2005) and, overall, is quite suited for modelling agriculture and food-industry systems. In fact, the authors found in it the supportive data to best model the system, though adjustments were needed in the farming-treatment modules. They were made by replacing the diesel-consumption values already contained within those modules with the ones provided by the firm, and the resulting emission values were updated subsequently.

Also, the emissions of both ammonia (NH_3) and dinitrogen monoxide (N_2O) resulting from administration of fertilisers have been estimated following the calculation procedure proposed by Brentrup et al. (2000).

For details regarding the primary and secondary data that were inventoried for the study development, the reader is referred to Tables 1–6.

Table 3
Inventories associated with the kneading phase.

Outputs			
Output product	*Amount*	*Unit of measure*	*Comment*
Dough	**1**	kg	This phase is referred to the preparation of 1 kg dough using the semolina produced. All inputs reported in this table are referred to the functional unit associated with the kneading phase, namely 1 kg of produced dough.
Inputs			
Materials	*Amount*	*Unit of measure*	*Comment*
Tap water	**0.351**	kg	
semolina	**0.540**		The semolina is produced in the milling phase, whose inputs and outputs are shown in Table 2.
Sourdough	**0.097**		The sourdough is daily prepared through the following refreshing process: one quarter of the sourdough produced the day before and stored under refrigeration conditions for 24 h,.is mixed with one part of water and two parts of semolina. The "new" dough that is so produced is left resting for 5 h before use in the kneading phase for the bread production of the day. Hence, for production of 1 kg sourdough, the following inputs were considered: 0.250 kg of water; 0.500 kg of DW semolina; and 0.250 kg of the sourdough prepared the previous day and refrigerated. Also, 0.0437 kWh of electricity are used in 1 kg sourdough preparation process (refrigeration + refreshment).
Electricity	**0.027**	kWh	This is the electricity required for the kneading of 1 kg dough using the raw materials and resources shown in this table.

Table 4
Inventories associated with production of bread loaves (Step-A).

Outputs			
Output product	*Amount*	*Unit of measure*	*Comment*
Bread loaves	**1**	kg	This phase is referred to the preparation of 1 kg bread following the phases of: shaping, leavening, baking, and cooling, as depicted in Fig. 2. All inputs reported in this table are referred to the functional unit associated with this phase, namely 1 kg sliced bread loaves.
Inputs			
Materials	*Amount*	*Unit of measure*	*Comment*
Dough	**1.34**	kg	This is produced following the process described in Table 3. The alongside value is depending upon the processing yield: 0.34 kg is the mass loss that is naturally manifested as a consequence of the baking phase.
Electricity	**0.1045**	kWh	This is the electricity required for 1 kg bread production, from dough shaping into loaves, to leavening, baking and cooling of those loaves.
Emissions in air	*Amount*	*Unit of measure*	*Comment*
Carbon dioxide (CO_2), biogenic	**23.3**	g	These emissions are associated with the fermentation process occurring during the dough leavening phase. For their estimation, the following assumptions were made: - starch content in semolina is around 70% (Stone, 1996); and - 1 kg of semolina corresponds to 1.45 kg bread, which contains about 45% starch (Sgrulletta et al., 2010). The starch loss is, then, 47.5 g starch per kg semolina: this fraction is enzymatically converted to maltose and glucose, which is further metabolised by yeasts into ethanol and CO_2, according to the following molar and mass relations: - 1 mol glucose → 2 mol ethanol +2 mol CO_2; - 180 g glucose → 92 g ethanol +88 g CO_2. Hence, the fermentation of 1 kg of semolina implies the transformation of 47.5 g starch, through glucose, into 24.2 g ethanol and 23.3 g CO_2.
Ethanol	**24.2**		

About the transports involved, the latter are just in the phases of cultivation and milling; for contrast, there are no transports in the other phases included in the bread production system because they are developed within the same plant. For completeness, Table 7 was reported to show the transport flows considered, together with the related diesel consumptions.

For more detail, Fig. 3 was reported to summarise the main system steps considered and the material flows (input/outputs) through which they are interconnected. The by-products associated with the phases of cultivation, milling and sliced-bread production were depicted in the figure as falling outside the system boundaries, and so were considered just as co-products through a mass-based allocation. The reader is reminded to Tables 1, 2 and 4 for details.

4.3. Impact assessment methodology application

4.3.1. Life Cycle Impact Assessment (LCIA)

This phase was conducted by aggregating in a limited set of Impact Categories (ICs) the output flows that had been previously quantified in the LCI phase (De Benedetto and Klemes, 2009). To that aim, the authors accessed and used the classification/characterisation framework provided by Impact (2002)+ (Jolliet et al., 2003): a comprehensive and valid impact assessment method which is often used in LCAs. Then, the ICs were grouped into Damage Categories (DCs): as is known, these are the environmental compartments that suffer the damage caused by the product in its life-cycle. The assessment was, hence, extended to the endpoint approach, which means that the phases of '*normalisation*' and '*weighing*' were developed.

In particular, the mid-point approach was used to quantify the LCIA results in the form of specific characterisation values represented by equivalent indicators like, for instance, $kgCO_{2eq}$ for '*Global Warming*', $kgPM_{2.5.eq}$ for '*Respiratory Inorganics*', and $kgC_2H_3Cl_{eq}$ for '*Carcinogens*'.

As regards the end-point approach, estimation of the '*weighing*' results were performed by means of equivalent numerical parameters that are usually expressed as '*weighing points*' or '*damage points*' or '*eco-points*' or, more simply, '*points*'. By doing so, this team of authors could represent quantitatively the environmental impacts associated not only with the system investigated but, also, with all the included processes and phases, that the most impacting ones could be highlighted. Following Lo Giudice et al. (2017) the

Table 5
Inventories associated with slicing of the produced bread loaves (Step-B).

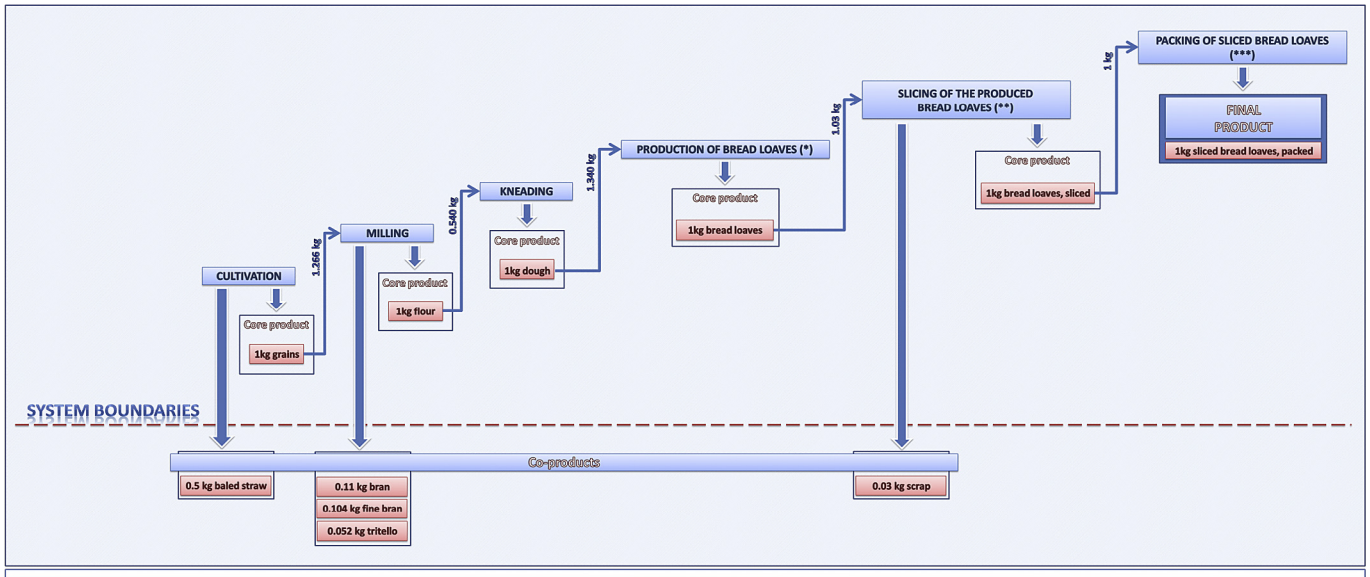
Outputs			
Output products	*Amount*	*Unit of measure*	*Comment*
Bread loaves, sliced	**1**	kg	This phase is referred to the phase of slicing 1 kg bread loaves that were produced in the Step-A, as shown in Table 4. All inputs reported in this table are referred to the functional unit associated with this phase, namely 1 kg bread loaves, sliced.
Scrap	**0.03**	kg	The scrap is subjected to a quite articulated process of transformation (into bread crumbs) that, however, was considered by the authors as falling outside the system boundaries, and so was not investigated. For this reason, the scrap was modelled as a co-product. A mass-based allocation was, so, applied for a correct distribution of both inputs, outputs and environmental impacts. The allocation percentages are: 97.09% for the sliced-bread; and 2.91% for the scrap resulting from the sliced-bread production process.
Inputs			
Materials	*Amount*	*Unit of measure*	*Comment*
Bread loaves	**1.03**	kg	These are produced in the Step-A of the entire system (see Table 4).
Electricity	**0.0089**	kWh	This is the electricity required for slicing.

Table 6
Inventories associated with the final process of sliced bread loaves packing (Step-C).

Outputs			
Output product	*Amount*	*Unit of measure*	*Comment*
Sliced bread loaves, packed	**1**	kg	This phase is referred to the packing of 1 kg sliced bread loaves, which is the functional unit of the whole system and to whom all the following inputs are related.
Inputs			
Resources	*Amount*	*Unit of measure*	*Comment*
Occupation, industrial built-up area	**0.0968**	m^2*y	The alongside value was calculated: by considering that: the production of the '*Pagnotta del Dittaino*' PDO represents the 25% of the whole firm production rate; the surface occupied by the whole factory is 19360 m^2; and the yearly production yield is around 50000 kg.
Materials	*Amount*	*Unit of measure*	*Comment*
Bread loaves, sliced	**1**	kg	These are from Step-B. All inputs that were indicated in this table are referred to the functional unit associated with this phase, namely 1 kg sliced bread loaves, packed. The latter can be considered as the final product of the whole system investigated.
Polymeric film	**3**	g	
Electricity	**0.018**	kWh	This is the electricity required for the packing process.

Table 7
Details on the transport flows considered for the whole system assessment.

Input material transported	*Transport flow (kgkm)*	*Related low-sulphur diesel consumption (kg)*	*Comment*
Seeds	**1.125**	**1.07E-4**	Transport flow associated with the supply of 0.075 kg of DW seeds, using a Euro-4 lorry with a 3.5–7.5 t capacity. The travelled distance is around 15 km, since the DW grain seed are locally produced.
Fertilisers and pesticide	**240.066**	**0.0177**	Transport for supply of the fertilisers (urea and diammonium phosphate) and pesticide, using a Euro-5 lorry with a 7.5–16 t capacity. The total amount transported is equal to 0.0667 kg, and the travelled distance is equal to 2000 km.
Grains	**18.99**	**1.804E-3**	Transport flow associated with the supply of 1.266 kg of DW grains, using a Euro-4 lorry with a 3.5–7.5 t capacity



Legend

The processes of bread loaf production (*), slicing (**), and packing (***) have been labelled as '*Step-A*', '*Step-B* and '*Step-C*', as also clarified in the headings of Tables 4-6. Those three steps encompass the following processes:

Step-A	**Shaping of the produced dough into loaves; and their leavening, baking and cooling. Based upon the model created, this step encompasses: DW cultivation; flour production through grain milling; and usage of that flour in the kneading phase for dough preparation.**
Step-B	**Slicing of the bread loaves produced in the previous step. Therefore, this step comprises the previous one, namely Step-A**
Step-C	**This is the final step, namely the packing, which includes the previous ones (Step-A and Step-B) and delivers the final product associated with the entire system: 1 kg packed, sliced bread loaves.**

According to the metodological approach that has been adopted in this LCA, each of the aforementioned steps, including those coming before Step-A, namely grain cultivation and milling, and dough preparation, are interconnected by the mass flow: the output of one step is the input to the next one.

Fig. 3. Summary of the main sub-systems and related interconnection mass flows.

Table 8
Global Warming Potential of relevant GHGs. Conversion factors from IPCC (2013).

GHG	Formula	GWP_{100} (gCO_{2eq}/gGHG)
Carbon dioxide	CO_2	1
Methane	CH_4	28
Nitrous oxide	N_2O	265

weighing points were obtained according to the Impact 2002 + framework, multiplying the dimensionless results from the '*normalisation*' phase by 1 pt. For clearness reasons, it is underscored that the latter represents the factor (equal for all DCs and ICs) to convert results from the '*normalisation*' to the '*weighing*' phase.

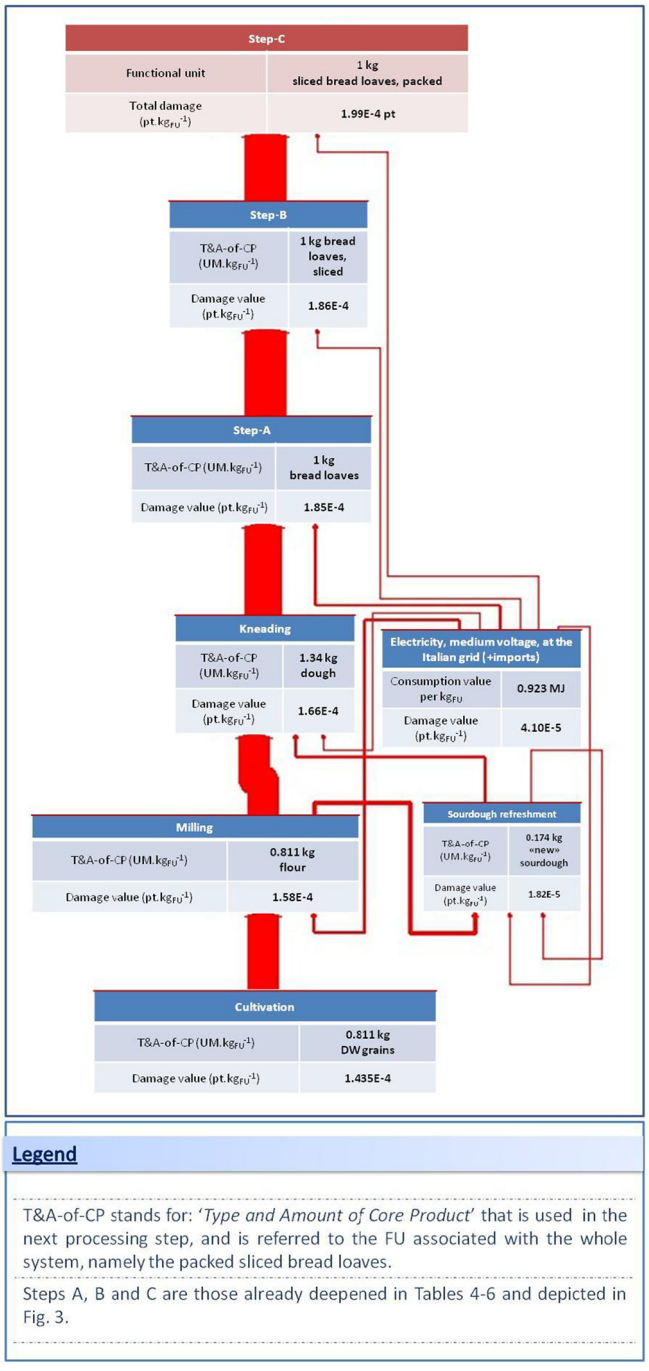


Fig. 4. Damage flow network.

4.3.2. Carbon Footprint (CF)

CF is a single-issue impact assessment that allows for the quantification of the environmental consequences of a given activity, process or product in terms of CO_2 equivalent (CO_{2eq}) emissions (Wiedmann and Minx, 2008; Maalouf et al., 2018). In this study, estimation was performed following the IPCC 2013 GWP 100a (IPCC, 2013), according to eq. (1) that was extrapolated from Maalouf et al. (2018):

$$EF_i = \sum_j GWP_j \cdot e_j \quad (1)$$

where.

- ej is the emission (in mass unit) of the j-th GHG associated with the given process;
- GWP_j is the Global Warming Potential of the j-th GHG for a 100-year temporal horizon (GWP_{100}), which is required for any CF assessment. In this regard, Table 8 reports the GWP_{100} of the GHGs that were considered by the authors to be most representative of the investigated system.

4.3.3. Cumulative Energy Demand (CED)

The CED is an impact indicator that expresses the energy utilisation throughout the life cycle of a good or a service (Hischier et al., 2010). So, it can be understood as an indicator of environmental impacts as far as the energy resource depletion is concerned (Gürzenich et al., 1999).

In this study, according to Wiesen and Wirges (2017), it was calculated as implemented in the Ecoinvent database, so considering all the given energy categories of non-renewable (fossil, nuclear, primary forest) and renewable (biomass, geothermal, solar, water, wind) energy.

Finally, the mid-point approach was conducted using the characterisation factors provided by Ecoinvent whilst, for the end-point approach, the Impact 2002 + weighing factors were considered, as discussed in section 4.3.1.

5. Results and discussion

5.1. Life Cycle Impact Assessment (LCIA) and CED analysis

The assessment highlighted that the total damage associated with the whole system investigated is equal to 1.99E-4 pt. In this regard, the damage network of Fig. 4 allows to understand that the highest damage flow arises from the cultivation phase with a value of 1.435E-4 pt. In addition, the consumption of medium-voltage electricity demanded by the processing steps, from semolina to bread loaves production, slicing and packing, including the sourdough refreshment contributes 4.1E-5 pt. The remaining materials and processes account for a total of 1.4E-5 pt.[2]

In addition, the CED analysis for the entire system highlighted that the energy sources considered account for a total of 21 MJ, which is due for 86.19% to the cultivation. So, considering the evidences from both the LCIA and the CED-analysis, cultivation can be considered as the phase requiring priority in the design, implementation and testing of improvement solutions.

For this reason, special attention and details were given to the discussion of the results deriving from the cultivation phase assessment (see section 5.1.1).

[2] Personal elaboration from Impact (2002)+.

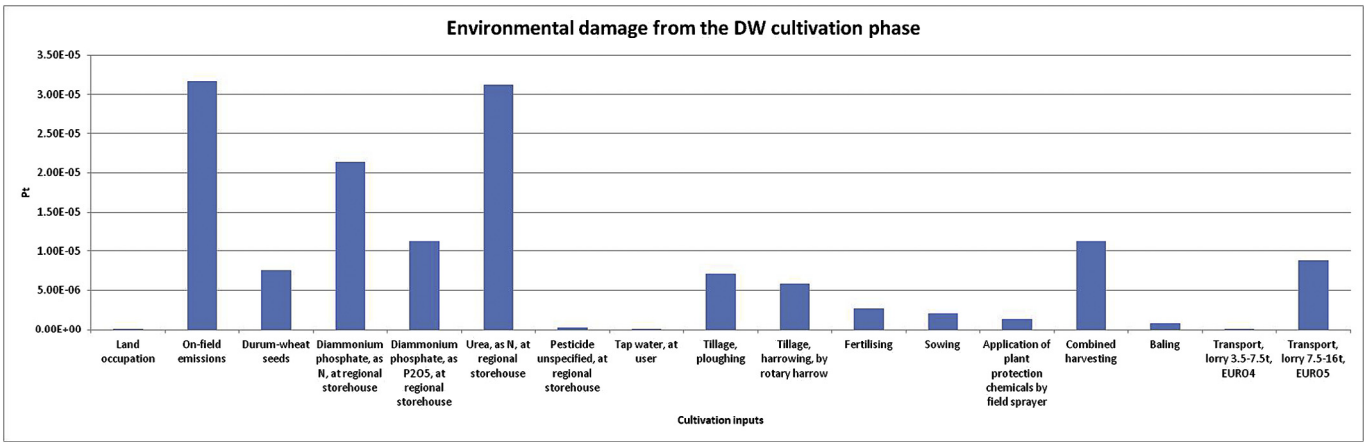


Fig. 5. Damage evaluation in the cultivation phase.

5.1.1. The cultivation phase

The LCIA as well as the CED assessment of the cultivation phase were performed and referred to the amount (0.811 kg) of DW grains that is required for production of the FU of the whole process, namely 1 kg packed sliced bread loaves.

Based upon the results obtained, it was observed that, as also shown in Fig. 5, the damage associated with this sub-system is equal to 1.435E-4 pt and is due for:[3]

- a total of 22.74% to the production of 0.0379 kg diammonium phosphate, as sum of as N and P_2O_5, as implied for the FU production;
- a total of 22.1% to the on-field emissions of NH_3 and N_2O occurring during mineral fertilisation;
- 21.8% to the production of urea in the amount associated with the FU of the whole system, namely 0.0303 kg;
- 21.79% to the total of the agricultural activities performed for treatment of 1.9 m^2 of soil per kg_{FU}, including the baling of the straw resulting from the harvesting;
- 6.12% to the total of transports for supply of both fertilisers and pesticides, with a transport flow equal to 0.137 $tkm.kg_{FU}^{-1}$; and

Entering into the merits of the DCs, the assessment pointed out that '*Human health*' (HH) is the one to be most affected, followed by '*Resources*' (R) and '*Climate change*' (CC); whilst, '*Ecosystem quality*' (EQ) is the one suffering the lowest environmental damage. For details, the related weighing results are shown in Table 9[4].

The most impacting resources consumed and substances emitted in air, water and soil were identified for each DC: results are shown in Fig. 6 for the end-point approach.

From Fig. 6 there is evidence that the most environmentally problematic substances emitted and resources used are: NH_3; particulates (with grain size less than 2.5 μm); nitrogen oxides; fossil CO_2; N_2O; and, gas natural and crude oil.

Their percent contributions to the damage associated with the related DC, as well as with the cultivation system (1.435E-4 pt) were shown in Table 10. It emerges, indeed, that they influence upon the damage associated with the cultivation system for a total of 82.01%. Therefore, they could be considered for identification of the most significant impact indicators to be used to:

- best represent and model the system investigated as well as other comparable crop-cultivation systems; and
- develop environmental labels, like the Environmental Product Declaration (EPD).

Table 9
Results from the weighing step per DC.

DC	Weighing score (E−5 pt)	Damages assessment	
		Value	*Unit of measure*
HH	**6.84**	**4.85E-7**	DALY [(a)]
R [(d)]	**3.42**	**5.2**	MJ primary
CC	**3.05**	**0.302** [(c)]	$kgCO_{2eq}$
EQ	**1.04**	**0.142**	$PDF*m^{2}*y$ [(b)]

[a] DALY (Disability-Adjusted Life Year): a measure of the overall severity of a disease, expressed as the number of years lost due to illness, disability or premature death.

[b] PDF (Potential Damage Fraction): the fraction of species that have a high probability of not surviving in the affected area due to unfavourable living conditions.

[c] Based upon the 2001-IPCC characterisation factors provided by Impact (2002)+ this value is referred to a 500-year time horizon. Therefore, this assessment does not replace but integrates the CF study that, instead, estimates the GHG emissions with a 100-year horizon.

[d] Following the classification scheme and methodology provided by Impact (2002)+ (Jolliet et al., 2003), the following ICs are grouped into *'Resources'* (R): *'Non-renewable Energy'*; and *'Mineral extraction'*. In this context, those associated with *'Resources'* are total values, though it can be concluded that they are entirely due to the use of non-renewable energy which, indeed, accounts for 99.81%.

The substances affecting *'Ecosystem Quality'* were not discussed, since they are characterised by largely lower damage rates. Moreover, in Table 11 the substances and resources shown in Table 10 were further detailed in terms of output inventory and mid-point approach results. Also, the percent contributions operated by the most impacting products and processes listed at the beginning of this sub-section were investigated.[5]

The most significant processes and issues amongst those shown in Table 11 are A, B and D for almost all the substances and resources considered. With regard to the total of the agricultural activities (D), the usage of natural gas should be attributed mainly to the life cycle (production, maintenance and disposal) of the agricultural machineries, considering the share related to the cultivation of 1.9 m^2 (surface invested for production of 0.811 kg of DW grains, as demanded for production of 1 kg packed sliced bread loaves). Hence, the low contribution from the agricultural activity to this substance compared to the others.

[3] Values were extrapolated from single-score evaluation in Impact (2002)+.
[4] Notes to Table 9.
[5] Notes to Table 11.

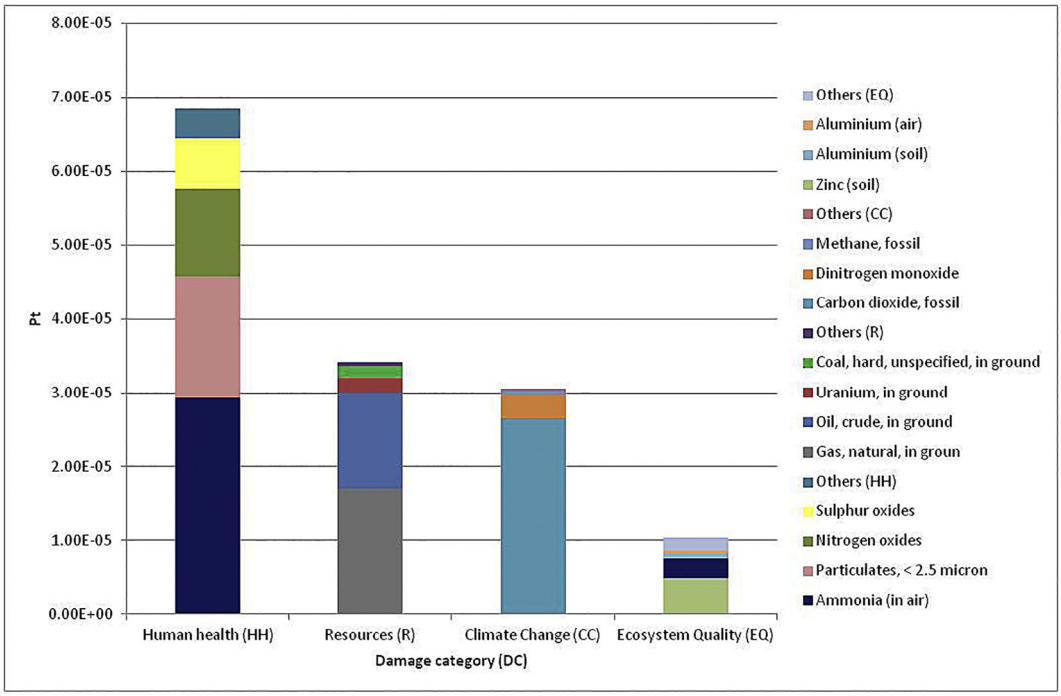


Fig. 6. Weighing phase: most damaging resources used and substances emitted per each DC considered. End-point approach results.

Table 10
Contributions made by the substances emitted and resources used that are most significant and representative of the cultivation system, to the damage associated with both the single DC and the cultivation phase. The assessment was conducted through elaboration of the weighing points (end-point approach).

Substance/resource	Percent (%) contribution to the damage associated with:	
	The given DC	Cultivation
Human health		
NH_3	**42.86**	**20.50**
Particulates (with grain size < 2.5 μm)	**23.91**	**11.44**
Nitrogen oxides	**17.44**	**8.34**
Resources		
Gas, natural, in ground	**50**	**11.94**
Oil, crude, in ground	**37.65**	**8.99**
Climate Change		
CO_2, fossil	**87.16**	**18.56**
N_20	**10.51**	**2.24**

The transport issue (E) has significant impacts just in terms of emission (in air) of nitrogen oxides and CO_2 as well as crude oil consumption, mainly because of diesel utilisation and combustion during lorry operations.

Seed production (C) contributes in all substances and resources with an average incidence of 5.21%.

NH_3 volatilisation occurs mainly as a consequence of the application of both diammonium phosphate (as N) and urea (for almost 90%). Similarly, the emission of N_2O is due to the application of those mineral fertilisers for approximately 92%, though its contribution to the cultivation stage is far lower than that made by NH_3: 2.24% vs. 20.50%.

With regard to the CED results, the following two energy impact categories resulted to be the most affected amongst those considered by the m2ethod: *'Renewable, biomass'*; and *'Non-renewable, fossil'*. They account for 71.6% and 26.3% of the total (18.1 MJ) of the energy sources investigated by CED. The former, with a characterisation value of 12.96 MJ, is due for almost 95% to the energy (gross calorific value) developed during the photosynthetic activity. This energy issue is not considered in Impact (2002)+, so remarking the importance of the CED analysis in this study as the way not to replace but integrate the whole LCIA. Whilst, the latter is characterised by an energy indicator equal to of 4.76 MJ, to which crude oil and natural gas contribute for 51.68% and 40.96%, respectively (see Table 11).

Finally, the assessment was extended to the ICs; the most impactful ones are: '*Respiratory Inorganics*'; '*Non-renewable energy*'; and '*Global warming*'. Both end-point and mid-point results are shown in Table 12.[6]

5.2. Carbon Footprint (CF)

From the assessment, the CF associated with the whole system investigated, as shown in Figs. 2 and 3, is equal to 0.496 $kgCO_{2eq}.kg_{FU}^{-1}$. It is due for nearly 67% to the production of 0.811 kg DW grains, as required for production of 1 kg packed sliced bread loaves. The CF value for cultivation was around 0.332 $kgCO_{2eq} \cdot kg_{FU}^{-1}$. In addition, the consumption of medium-voltage electricity associated with the entire process, from grain milling to sliced bread loaves packing, contributes for 29.8% to the total CF associated with the whole system.

Results are comparable with those from Ruini and Marino (2010) who documented a CF value of 610 $kgCO_{2eq}.t^{-1}$, mainly due to the use of plant fertilisation and protection chemicals. Differences between the two studies should be attributed to different soil and climate conditions, farming systems and, also, to the evaluation

[6] This was estimated through CED application taking into account only the fossil share of the non-renewable energy. The other shares, namely the nuclear and biomass ones according to the CED calculation method in Ecoinvent, were neglected due to the low contributions compared to the fossil share. The latter represents, indeed, 93.92% of the total non-renewable energy amount.

Table 11
Output inventory and characterisation (mid-point approach) values for each of the most impacting substances and resources listed in Table 10. In addition, the percent contributions coming from the most impacting processes were reported, too.

Substance/resource	Output inventory		Characterisation		Percent (%) contribution made by the most impacting processes ([a])
	Value	Unit of measure	Value	Unit of measure	
Human health					
NH_3	**2.44**	g	**1.25**	$kgC_2H_3Cl_{eq}$	- 89.7% (F); - 5% (C); - 4.15% (A); - Negligible contributions were observed highlighted for the (B), (D) and (E) processes.
Particulates (with grain size < 2.5 μm)	**0.166**		**1.66**	$kgP.M_{2.5eq}$	- 35.25% (D); - 31.5% (B); - 24.9% (A); - 5.17% (C); - 3.12% (E).
Nitrogen oxides	**0.955**		**1.22**		- 54.84% (D); - 17.36% (B); - 11.9% (A); - 10.2% (E); - 5.32% (C).
Resources ([b])					
Gas, natural, in ground	**64.4**	l	**2.46**	MJ	- 53.3% (A); - 36.68% (B); - 5.23% (C); - 3.17% (D); - 1.43% (E).
Oil, crude, in ground	**42.54**	g	**1.95**		- 32.12% (D); - 21.95% (B); - 20.3% (A); - 19.9% (E); - 5.32% (C).
Climate Change					
CO_2, fossil	**263.68**	g	**263.68**	gCO_{2eq}	- 33.8% (A); - 29.82% (B); - 20.11% (D); - 10.5% (E); - 5.38% (C).
N_2O	**0.203**		**0.0317**		- 92.3% (F); - 5.02% (C); - Negligible contributions were found for the (A), (B), (D) and (E) processes.

[a] These processes are those affecting the damage associated with the cultivation step, namely 1.435E-4 pt, for a total of 95–100%; they are: (A): urea production; (B): production of di-ammonium phosphate as sum of as N and P_2O_5; (C): seed production; (D): total of the agricultural activities, including the straw baling; (E): transport for supply of both fertilisers and pesticides; and (F): on-field N_2O-emissions due to fertilisation.
[b] The mid-point approach values for both natural gas and crude oil were calculated by the CED analysis, thus using the following characterisation factors: 38.3 $MJ(m^3)^{-1}$, for the former; and 45.80 MJ kg^{-1}, for the latter, as reported by (Hischier et al., 2010).

Table 12
Weighing points and characterisation values for each of the most impactful ICs.

IC	Weighing point	Characterisation value	Unit of measure
Respiratory Inorganics (RI)	6.44E-5	6.52E-4	$kgPM_{2.5eq}$
Non-renewable Energy (NRE)	3.419E-5	4.76	MJ
Global Warming (GW)	3.05E-5	0.302	$kgCO_{2eq}$

methods (CF, 2007 vs 2013). Entering into the merits of the main gases shown in Table 8, the contribution made by the cultivation phase to the entire system was investigated in terms of values of both inventory emissions and GWP_{100} (Fig. 7). The latter was calculated from the former following Eq. (1) and using the conversion factors listed in Table 8.

Based upon the GWP_{100} factors used for the assessment (see Table 8), N_2O and CH_4 have higher effects upon the global warming compared to CO_2. However, the emitted amounts of CO_2 are so greater than the amounts of the other two gases that it can be considered as the most significant, representative GHG of the entire system, as well as of the cultivation. Indeed, based upon Fig. 7, CO_2 contributes for nearly 85% and 80% to the CF of the whole system and the cultivation stage, respectively.

Finally, the percent incidence played by cultivation on the whole system is equal to: nearly 63% for CO_2; almost 98% for N_2O; and around 67% for CH_4. The highest contribution that was recorded for the case of N_2O should be attributed to the related on-field emissions occurring during crop production as a result of the mineral fertilisation. Significant emission sources in the other system phases were not observed for N_2O. For contrast, they were for CO_2 and CH_4, though cultivation remains the most impacting phase and, so, the most relevant issue for either of the two gases.

Furthermore, the hystogram of Fig. 8 shows the processes that most contribute to the CF related to the cultivation phase, considering the total value and the values associated with each of three accounted GHGs.

Table 13 shows the percent contribution that is made by each of the processes depicted in Fig. 8, to the CFs associated with all the three GHGs as well as to the total CF recorded for the cultivation

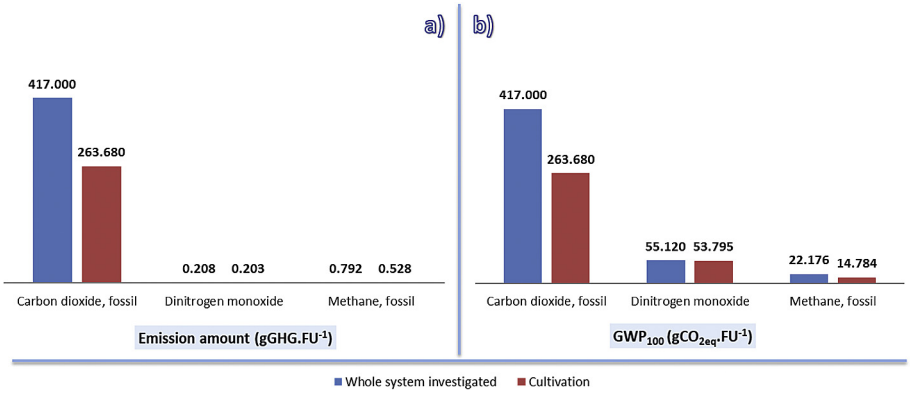
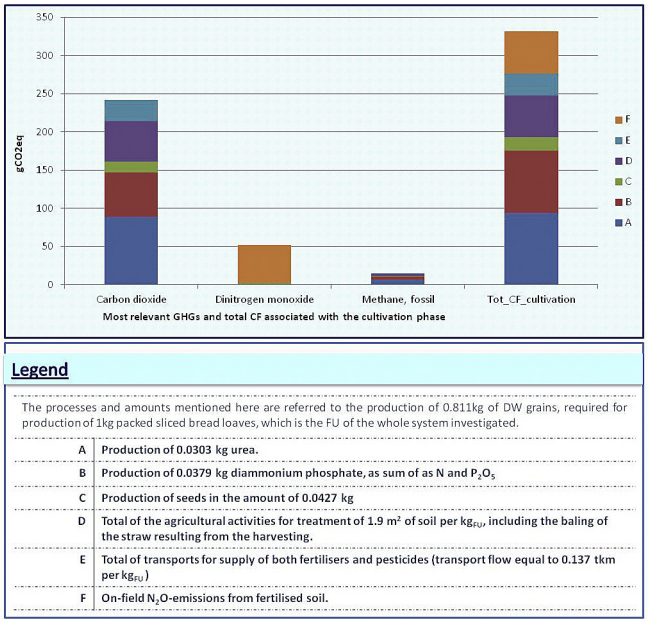


Fig. 7. Assessment of the contribution made by the cultivation to the whole system: based upon the emission amounts of the most relevant GHGs (a), and the GWP_{100} values associated with the most relevant GHGs (b).



Legend

The processes and amounts mentioned here are referred to the production of 0.811kg of DW grains, required for production of 1kg packed sliced bread loaves, which is the FU of the whole system investigated.

A	Production of 0.0303 kg urea.
B	Production of 0.0379 kg diammonium phosphate, as sum of as N and P_2O_5
C	Production of seeds in the amount of 0.0427 kg
D	Total of the agricultural activities for treatment of 1.9 m^2 of soil per kg_{FU}, including the baling of the straw resulting from the harvesting.
E	Total of transports for supply of both fertilisers and pesticides (transport flow equal to 0.137 tkm per kg_{FU})
F	On-field N_2O-emissions from fertilised soil.

Fig. 8. Cultivation phase: assessment of the total GWP_{100} and of the GWP_{100} associated with each of the most relevant and representative GHGs of the whole system.

Table 13
Analysis of the contribution that the most relevant processes within the cultivation phase (see Fig. 8) make to the GWP_{100} associated with the three gases considered as well as with the related total-CF (CF_{tot_cultiv}).

GHG	GWP_{100} (gCO_{2eq})	A	B	C	D	E	F
		Contribution to the alongside GWP_{100} (%)					
CO_2	263.68	33.8	21.82	5.38	20.11	10.5	x
N_2O	53.795	—	—	5.02	—	—	92.3
CH_4	14.784	43.1	30.07	5.29	14.26	6.73	x
CF_{tot_cultiv}	332.26	28.2	24.6	5.32	16.44	8.62	16.5

x = no contribution made by the process to the given GHG emission; — = contribution less than 1%, considered as negligible.

phase (CF_{tot_cultiv}).[7]

From interpretation of Table 13, it results that the total of the processes considered (from A to F) contributes to the CFs associated with the three GHGs (from C_2O to CH_4), as well as with cultivation phase, for: 91.61%; 97.32%; 99.45%; and 99.68%. This is in line with the LCIA and confirms that those processes are the most relevant ones and so represent the environmental hotspots on which to focalise for operating improvements.

In particular, in agreement with the LCIA, the highest contributions are in the production of urea (A) and diammonium phosphate (B), as well as in the agricultural activities (D) that are developed for crop production.

Furthermore, there is evidence that.

- comparable contribution values were recorded for seed production (C);
- the impact from transports (E) is manifested more through emission of CO_2 than of CH_4. No relevant emission of N_2O was correctly recorded for this process; and
- the greatest contribution to N_2O-GWP_{100} is made by the related on-field emissions occurring as a consequence of the fertilisation activities.

Finally, calculation of the CF associated with each GHG considered as well as with the whole system investigated was extended to the third and fourth IPCC Assessment Report (AR) (Table 14). The resulting values were compared to those obtained according to the fifth AR. AR-3 and AR-4 were taken into consideration for the comparison, because the related GWP_{100} factors are still used for inventory and reporting purposes. In the particular case, this could favour comparisons with studies from the subject literature where CF was applied to similar bakery products using the GWP_{100} values from those two ARs.

Different GWP_{100} values were recorded, as a consequence of the different conversion factors that were defined and delivered through the various IPCC-ARs. This is just for N_2O and CH_4, because

Table 14
Comparison of CF-values calculated according to Eq. (1) but using the conversion factors established in the previous IPCC Assessment Reports (ARs). CF values related to the whole system investigated, and so referred to its FU, namely 1 kg packed sliced bread loaves.

GHG	2001-IPCC (3rd AR)	2007-IPCC (4th AR)	2013-IPCC (5th AR)
	GWP_{100} (gCO_{2eq})		
CO_2	417		
N_2O	61.57	62.1	55.12
CH_4	18.22	19.8	22.18
Tot. CF	**496.79**	**500.11**	**480.09**

[7] Notes to Table 13.

CO_2, confirmed as the most contributing GHG, remains the reference gas with an unchanged conversion factor equal to 1 gCO_{2eq}/gCO_2.

6. Conclusions

This study was conceived to investigate the production of a Sicilian PDO DW bread, called *'Pagnotta del Dittaino'*, which is generally marketed in the form of packed sliced bread loaves. The study was focussed upon the assessment with an LCA approach of: global environmental impact; emissions of GHGs with a 100-year time horizon, namely the CF; and primary energy sources using the CED-analysis.

The study highlighted that the main impacting phase is cultivation, mostly because of the production of urea and diammonium phosphate, and of the agricultural activities performed. Significant contributions come from NH_3 volatilisation and nitrous oxide emission due to the mineral fertilisation conducted for crop production, so impacting upon *'Human health'* and *'Climate Change'*. The impact to '*Resources*' is manifested through the non-renewable energy use, principally because of the consumption of natural gas and crude oil which derive from: the production of the aforementioned mineral fertilisers; the agricultural activities; and the transport for supply of those fertilisers.

Additionally, the CED-analysis allowed to point out the important contribution coming from the use of biomass energy, as a consequence of the energy that is sequestered by the plant during its growth, and is represented by its gross calorific value. As regards CF, the study confirms that CO_2 is the most relevant and representative GHG in this (and similar) food system, which, as a matter of fact, is increasingly taken as a key indicator for the implementation of environmental strategies and policies.

Due to the peculiarity of the studied system and to the lack of specific literature on DW breads, comparisons with other studies were limited mainly to general considerations on the life cycle of cereal-derived products. In particular, in agreement with previous literature, it was highlighted that the main impacts are in the production and administration of fertilisers and other agricultural activities.

Based upon the obtained results, improvements could be made in the cultivation phase, for instance by: resorting to conservative farming systems; partly or totally replacing chemical fertilisers with less-impacting ones; shifting to an organic fertilisation regime. The technological and environmental feasibility of such solutions may be evaluated in the future upon discussion with the farmers and agronomists involved.

Finally, the study offers: *i*) a comprehensive dataset resulting from the efforts spent on collecting site-specific data (primary data) and combining them with available secondary data (Ecoinvent); *ii*) a critical, in-depth analysis and interpretation of results from the environmental and energy assessment. Hence, results could contribute to the enrichment of knowledge and literature in the field and be of interest for researchers, LCA practitioners, farmers, producers, stakeholders and policy makers. It could also support the implementation of EPDs, thus giving added value to high-quality breads that, through the PDO-label, are strictly interconnected with local territories and significantly contribute to regional agro-economies.

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